# DESIGN AND OPERATION OF IRRIGATION SYSTEMS FOR CONJUNCTIVE WATER MANAGEMENT

**KRISHNA KUMAR SAKSENA**

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HAUZ KHAS, NEW DELHI-110016 INDIA

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# CERTIFICATE

It is certified that this thesis titled '***Design and Operation of Irrigation Systems for Conjunctive Water Management***' submitted by **Mr. K.K. Saksena** to the **Indian Institute of Technology, Delhi**, India for award of the degree of **Doctor of Philosophy**, is a bonafide research work carried out by him under my supervision. The work in my opinion, has reached the standard fulfilling the requirements of the Ph.D degree. The report and the results presented therein have not been submitted, in part or full, to any other University or Institute for award of any other degree.

5/7/86


(Dr. A.K. Gosain)
Assistant Professor
Department of Civil Engineering
Indian Institute of Technology, Delhi.
Hauz Khas, New Delhi - 110 016
India.

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(K.K Saksena)

# SYNOPSIS

Irrigation management is probably the weakest limb of the irrigation systems not only in India, but world over. Huge amounts of money are invested on creation of irrigation facilities. The returns however, have not been commensurate. The irrigation water is neither efficiently, nor productively used. As a result, there exists a continued gap between the irrigation potential created and utilisation thereof. Also, the yield levels remain below expectations. Need for efficient management of irrigation water on the canal system, below the irrigation outlets and in the field during application is therefore, evident. The other but no less crucial factor in improving the performance of irrigation systems is matching the water deliveries to suit the consumptive requirements of the crops grown which vary with crops as also with stage of growth of crops. Water is a critical crop production input. When properly managed together with other inputs like improved seeds, fertilizers, plant protection measures, better package of cultural practices, etc. will bring manifold increase in existing crop productivity levels. This work therefore, in the first instance aims at devising suitable methodology for crop oriented irrigation management. Such a management of irrigation water however, requires the irrigation projects to be designed in a manner that the available supply fairly matches the temporally fluctuating water demand of the proposed cropping pattern. The work therefore, handles the design and operation of irrigation project in an integrated manner.

Irrigation has been considered a necessity in arid and semi-arid areas, a complementary process in sub-humid areas and only supplementary in humid areas. The humid areas do have more of a drainage problem than the need for irrigation. Further, the introduction of canal irrigation in any area alters the ground water regime of that area. Based on how best the canal water is managed, the topographic features of the command area, the sub-surface geology and the soil conditions, the altered ground water regime can prove to be detrimental to crop culture if watertable rises within the root zone soil profile. Fine or heavy textured soils are generally prone to waterlogging. Such soils with deep profile store sufficient water to permit growing of a post-monsoon season crop on residual moisture. When irrigation projects are constructed without considering these aspects, ill-effects on soil health and environment as consequences become inevitable. The suitability of any area for irrigation should therefore, be judged first looking at the soil-climate-vegetation complex of that area. This aspect has been included in this work as a pre-requisite to design and operation in terms of irrigation need assessment. However, when waterlogging develops, conjunctive use of surface and ground water can be taken up. Such a proposition will be beneficial in two ways. It will improve the design cropping pattern of the project as there always exists such a possibility in most surface water projects. Side by side, it will provide the vertical drainage to the waterlogged areas of the project command. The conjunctive use aspect thus forms another important component of this work.

The entire work has therefore, been divided into three principal components which include the following.

(i) Irrigation Need Assessment

(ii) Design and Operation of Irrigation Projects

(iii) Conjunctive use of Canal and Ground Water.

The first component virtually encompasses the use of incident rain in crop production in conjunction with irrigation water. The second component is further separated in (i) design of irrigation systems (only agri-irrigational aspects viz. crops, crop water requirements and cropping pattern are handled) and (ii) operation of irrigation schemes (both demand-based or crop oriented irrigation management and supply-based irrigation are covered). The second and third components complement each other in maintaining environment and soil health.

Irrigation Need Assessment is carried out in two inter- related stages. First, a water balance of the area on monthly basis is formulated taking into consideration the capacity of the soil to store water available for plant use. The elements of this water balance are historical monthly rainfall, monthly atmospheric evapotranspiration demand (potential or reference evapotranspiration) computed from historical monthly climatic data and the water holding capacity of soil. A comparison of the monthly rainfall vis-a-vis monthly potential evapotranspiration and the water holding capacity determines the months of deficit or surplus from the point of view of soil water availability for crop use. The months showing deficit indicate the need for irrigation. In the second stage, the rainfall of surplus months, which are essentially the monsoon (wet season) months, is further analysed to determine if there exist critical dry spells which will necessitate application of irrigation water to the crops. This analysis is performed using the historical daily rainfall data. The other factors of consideration here are the average daily atmospheric evapotranspiration demand of the area during these months and the number of days of break in rain which will make the break a critical dry spell from the standpoint of soils and crops of the area. The onset of effective monsoon (its latest probable, mean and earliest probable dates), the mean date of its withdrawal, the rainfall amounts of the wet spells and the weekly and monthly distribution of rainfall, are also determined for the project area. These characteristics decide the crops, their optimal sowing time and the timings during which irrigation water has to be available as well as permit efficient use of the rainfall in crop production.

In the Project Design and Operation component, the design is again based on historical climatic data. The design steps involved include (i) selection of suitable crops, considering the land capability, soil irrigability, agro-climatology and other relevant factors, (ii) determination of atmospheric evapotranspiration demand of the area, (iii) conversion of this demand into crop evapotranspiration and subsequently to project irrigation requirements taking into consideration effective rainfall, ground water contribution, pre-irrigation requirement, efficiency of irrigation, etc. and (iv) allocation of area under crops taking into consideration the land availability, water availability and proper mix of cereals, pulses, oilseeds, vegetables and other crops. Thus the cropping pattern to be fed from the available project water and the probable effective rainfall is designed for the project. The cropping pattern is designed using linear programming optimisation technique. The optimisation is done in terms of maximisation of profit, net of cost from the allocated areas subject to the above mentioned constraints.

A 75 % dependable level of rainfall is used in project design. Again, a part of this has been taken to be effective in meeting crop water requirements. Since with a dependable level of rainfall used in design of the cropping pattern, there is always a risk of failure of the supply vis-a-vis demand, a risk analysis in terms of the 'reliability' and 'vulnerability' of the project for an increased level of dependability has also been carried out.

For operation of the projects, a three-stage operation schedule is developed which is composed of:

(i) field irrigation schedule,

(ii) farm irrigation schedule and

(iii) project irrigation schedule.

The field irrigation schedule consists in determining when to irrigate and how much water to apply in each irrigation for individual crops? It is thus, essentially a schedule of irrigation of various crops grown in the project area. The farm irrigation schedule is the schedule of distribution of water among the individual farm holdings, growing different crops within the outlet commands. 'Time multiplied discharge equals area multiplied depth' is the basis of this schedule. The depth for a given frequency is obtained from the crop irrigation schedule. Project irrigation schedule determines the running schedule of the canal system above the irrigation outlet.

The crop irrigation schedules in terms of depth and interval of irrigations over the growing season have been computed adopting the three methods of:

(i) variable frequency:variable depth,

(ii) variable frequency:constant depth and

(iii) constant frequency:variable depth.

The three methods essentially involve computation of crop plot's water balance with effective rainfall, ground water contribution and stored soil water constituting the gain and crop evapotranspiration, the loss. This loss minus gain represents the depth to be applied. This depth divided by crop evapotranspiration rate gives the interval between two waterings. Such a computation essentially gives a crop irrigation schedule in which the frequency as well as depth of irrigations vary over the growing season. Though it may be called an optimal water regime from the point of view of plant nourishment, it needs to be rationalised taking into account the constraints exerted by the irrigation system. Two such rational approaches may be (i) keeping the frequency constant but varying the depth or (ii) making the depth of irrigation constant and computing the desired interval to offset the loss of water in evapotranspiration. The first of these two modifications suits the surface water schemes where rotational running of canal system is largely followed. The second suits to the ground water schemes, where water can be tapped as and when required and supplying water at various points of time during the crop period is not a problem.

The project operation is based on the data of the year of normal rainfall (normal hydrologic condition) rather than the complete historical data series. The effective rainfall in these computations has therefore, been calculated using USSCS method of normal effective rainfall as related to monthly rainfall and monthly consumptive use rather than the probability criteria used in design. The ground water contribution is based on Shaumyan method. The stored soil water at the beginning of crop growing season is calculated taking into consideration the rainfall or the pre-sowing watering (when the rainfall before the crop sowing is not enough to bring the soil to field capacity).

The irrigation scheduling of crops is normally done using total available soil water and the fraction to which this can be reduced by crops without affecting physiological processes. The total available soil water is the difference in water content at field capacity and the wilting point. The soil moisture tension is 0.1-0.3 bar at field capacity and ranges from 7 to 32 bar for the wilting point. This very wide range of soil moisture tension at wilting point leaves a question mark on the desirability of this concept, even though well established. Therefore, in this work an attempt has been made to introduce a modified concept in which 'total available soil water' has been replaced by 'water content in soil at field capacity' and the 'fraction to which the total available soil water can be reduced' by the 'fraction to which water content at field capacity can be reduced' by crops without affecting their physiological development i.e. without restricting the potential evapotranspiration. This eliminates the consideration of wilting point in scheduling of irrigations. The value to which soil moisture can be reduced below the field capacity by the crops has been judiciously selected considering the osmotic pressure of their root systems which enables them to suck the water from the soil. A comparison between the two approaches has been done to analyse the adoptability of the modified concept. Further, the concept of 'minimum spreadable depth' has also been introduced as watering depth lower than a certain minimum can not be applied in the field uniformly using the conventional water application methods.

The farm irrigation scheduling, i.e. the irrigation schedule for the field plots growing different crops in the outlet commands, has been done for (i) every week irrigation and (ii) alternate week irrigation (i.e. 7 or 14 day interval of irrigation). The period of irrigation of the outlet command is however, a week viz. the irrigation in an outlet command has to be completed within 168 hours, be it a every week or alternate week supply. The time to irrigate a field plot of given size growing a given crop with a given stream size has been arrived at by dividing the volume of water required per rotation with the outlet discharge. To this basic time of individual field plots are adjusted the conveyance/seepage loss in field channels from the outlet to the field and the time required for water to travel in the channel from the previous field plot (from the outlet in case of first plot) to the field plot to be irrigated, taking order of turns from head to tail of the outlet command. The volume of water for individual crop plots per rotation has been determined by dividing monthly volume computed using any of the above listed three methods of crop irrigation scheduling, but preferably the constant frequency:variable depth method by 4 in case of every week delivery and by 2 in case of alternate week delivery. The farm irrigation schedule thus gives the irrigation period of each outlet command within the period of rotation.

The schedule varies every month as the volumetric requirement varies month wise depending upon crop water requirements. However, within a month, all the four (or two in case of alternate week supply) schedules will have same timings for individual crop plots. The similar procedure can be used for crop oriented irrigation in tubewell commands for ground water schemes. It may be mentioned that the area served by an irrigation outlet has to be correlated to the outlet discharge (stream size for irrigation). The operational stream size is basically a function of soil type. The coarse textured soils require larger stream size in comparison to heavy textured soils because of their larger infiltration capacity. The water application depth in each irrigation normally varies from 50-100 mm. The outlet command area will thus, vary farm 17-34 ha for an outlet discharge of 28.3 lps (or 1.0 cusec which is considered appropriate for medium soils) in order that the entire area is covered under irrigation in 168 hours of rotation period. The clubbing of one or more outlets for irrigation may thus be done in case their irrigation periods collectively, are less than 168 hours.

The on-demand irrigation aiming at meeting crop consumptive needs in its strict sense will mean availability of irrigation water (i) at any point of time, (ii) for any duration and (iii) optionally at any stream size. But such a water delivery is not feasible under the existing irrigation projects in India and many others world over. Therefore, the above methodology has been devised in this work for the demand-based irrigation with a view to offset the crop evapotranspiration losses, as closely as possible if not exactly, under the denomination to crop oriented irrigation management.

The project irrigation schedule which involves determining the on-off timings of the canal system is devised from the computed irrigation periods of the offtaking channels. The irrigation periods of different outlet commands on a particular minor canal are determined in farm irrigation schedules. The turns of individual farmers (or crop plots) in each outlet command are summed up for determining the irrigation period of the outlet command during a particular rotation. The maximum among the irrigation periods of the off-takes together with the response time of the parent channel (time for water to travel from head of parent channel to its last outlet/tail end) determines the 'on-time' of the parent canal. The difference between the rotation period and the on-time determines the off-time of the parent channel. For the purpose of project irrigation scheduling, the entire distribution network down to the irrigation outlet has been considered in five stages (i) Demand Point (Outlet head), (ii) Demand Subnode (Minor Canal head), (iii) Demand Node (Distributary Canal head) (iv) Demand Subcentre (Branch Canal head), and(v) Demand Centre (Main Canal head). The response time therefore is to be calculated for (i) Demand Point:Subnode Link, (ii) Demand Subnode:Node Link, (iii) Demand Node:Subcentre Link and Demand Subcentre:Centre Link. For determining the on-off timings of distributaries, branches and main canals; the minors, distributaries and branches become the off-takes respectively; the response time is determined respectively for demand subnode:node link, demand node:subcentre link and the demand subcentre:centre link. The parent canal too has to be run for the required discharge (to match the consumptive requirements of crops grown). Adequate cross regulation of water on the parent canal is thus, required to ensure design discharge through the outlet.

The supply-based irrigation management has also been attempted in this work, besides the above discussed demand-based irrigation. This management has been done in two stages. The first stage involves distribution of water in the outlet commands. The equity in distribution is the cardinal principle of this approach. The equitable distribution is considered in two distinct ways (i) man- based equity and land-based equity. In the later approach, which is widely practised in India under the denomination of warabandi, the available water is distributed equally among the land holders in outlet commands in proportion to their areas of holding on rotational basis. In this method, those who own more land get more water even when they have not paid for creation of the irrigation facility. Therefore, the former is introduced as an alternative keeping social angle in mind. In this, water is distributed equally without considering the areas of land holdings. The approach can however, initially better suit the small village irrigation schemes in which water can be supplied to each family (owning or even not owning land) residing in the village. The turn-schedules for equitable distribution have therefore, been determined for both the methods. A 7-day rotation period is considered within the outlet commands. The basic time of water availability of a field in outlet command in land-based distribution has been calculated by dividing the period of water availability per rotation (168 hours) with the area of the outlet command and multiplying by its area (in contradistinction to the demand-based system where it is determined by dividing the water requirement per rotation by the outlet discharge). The travel time and conveyance losses are then adjusted to determine the lengths of turn which are allocated in terms of day, duration and time of supply. In man-based distribution, the basic time is obtained by dividing the period of rotation by number of beneficiaries. This is then converted into hours and minutes directly and then in day, duration and time of supply to each beneficiary person/ family with out considering the conveyance loss and travel time.

The second stage involves the regulation of water on the canal system above the irrigation outlets. This is also done in two different ways. In the first, the entire canal system from which the direct irrigation takes place (i.e. those canals which are provided with irrigation outlets) is divided in 2 or 3 groups depending on the selected interval of watering (considering crops and soils and also water availability vis-a-vis demand in case of water shortage). Since the rotation period of outlet commands is a week, the interval of irrigation is selected as multiples of the week. Thus, two groups are formed when interval of irrigation is selected as two weeks and three groups are formed when the selected interval is three weeks. The roastering of canals is then done for an equitable distribution of available supply over the entire command area in a manner that each group gets water in a preferential order one after the other through the cropping season. This roastering of canal has been done for 1 in 2 running (one week 'on' in two weeks) though 1 in 3 running, 2 in 3 running and a 3 in 5 running to suit the required interval and convenience of water distribution can also be attempted. In fact, the response time above the outlet (time for water to travel from head of a canal to its tail end) has also to be considered in devising the canal running schedules. As such, the canal system is made to run on a longer cycle (8-day) than the rotation cycle of the outlets (7-day). And this provides a safe 7-day period to the outlet commands to complete their irrigation. The response time can however, be also determined taking into consideration the lengths of canals and their flow velocities.

This type of canal regulation distributes the available supplies under the project in a more or less rigid mathematical manner. It is well known that crop water needs keep pulsating over the growing season and that certain of the crop growth stages are more sensitive to water stress. The availability of water during such stages should be ensured if the growth and yield processes have to go unhampered. In this work therefore, as an alternative the second approach has also been devised. In this, the canal operation schedule has been developed according to critical stages of crop growth yet providing equity in distribution of water over the command area, for the supply-based irrigation.

The conjunctive use model is composed of three parts. In the first, the response of the ground water system to the introduction of canal irrigation is assessed in terms of spatial distribution of watertable elevations at two discrete points in time i.e. pre-monsoon (May end) and the post-monsoon (October end) periods through aquifer response modelling. Thus, the areas likely to be waterlogged are delineated within the study area. In the second, the feasibility of lowering watertable in waterlogged portions of the command area is examined by way of improvement to the design cropping pattern of the project such that there is neither excessive rise nor lowering of watertable in the project area. The improvement to cropping pattern is done utilising linear programming optimisation technique used earlier for designing the cropping pattern of the surface water project taking into consideration the slots available for extending cropped areas and the augmented total water availability (surface water plus extractable ground water). The ground water development to meet the requirements of the additional cropped areas is the optimum level of ground water withdrawal for conjunctive use. For this level of ground water development, a well field is designed for waterlogged areas in the third stage. The well field design involves well arrangement, well spacing, drawdown and interference of wells, area which can be served by the wells and the running schedule of wells. This step also involves the selection of suitable ground water structures taking into consideration the hydrogeology of the area.

The aquifer response study is done for the normal hydrologic conditions. The pre-monsoon (May end) watertable data of the normal rainfall year in pre-project period is used as the initial condition. The model is run for a 10-year period beginning with the initial condition to determine the time to reach new dynamic equilibrium after induction of canal water and to delineate the waterlogged areas. In the subsequent run with improved cropping for determining reduction in waterlogging, the water requirement of additional cropped areas for the normal rainfall year in post-project period has been used.

Three computer based models namely (i) Irrigation Need Assessment (INA) model, (ii) Design and Operation (DAO) Model and (iii) Conjunctive Groundwater Use (CGU) Model have been developed for the aforesaid study. These models comprise a number of modules which include (i) Atmospheric Evapotranspiration Demand (AED), (ii) Monthly Soil Water Balance (MWB), (iii) Critical Dry Spell (CDS), (iv) Irrigation Requirement and Scheduling (IRS), (v) Crop Area Allocation (CAA), (vi) Farm Irrigation Scheduling (FIS), (vii) Project Irrigation Scheduling (PIS), (viii) Supply Based Irrigation (SBI), (ix) Groundwater Regime Simulation (GRS) and (x) Well Field Design (WDN).

The emphasis in this work has been on developing generic modules using simple yet comprehensive methodologies that can be used for obtaining a better output from existing irrigation projects as well as for planning new projects for productivity oriented irrigation and to test them for applicability under field conditions. The concepts elaborated above are therefore, applied to an irrigation project namely, Giri Irrigation Project for this study. This project is located in Paonta Saheb block of Sirmaur district of Himachal Pradesh state of India. These concepts can however, be equally used for ground water schemes in which case the outlet commands of the surface water project can be considered analogous to the tubewell commands.

It has been concluded from the work that Paonta Valley requires creation of irrigation facility to produce winter and summer crops as soil water deficit is found to exist during these months and even to sustain monsoon season crops as 2-3 critical dry spells occur in the area on an average. It has been further concluded that ground water regime of the area undergoes a change with the creation of irrigation facility and that the new dynamic equilibrium established results in rise of watertable in the project command necessitating ground water withdrawal for conjunctive use.

However, the waterlogged area also needs horizontal sub-surface drainage as the improved cropping could not relieve the waterlogging problem completely. With regard to design of the irrigation project, it is concluded that (i) modified Penman method can form a suitable base for determining the crop water requirements, (ii) linear programming can be used for allocation of area under different crops under full supply conditions (viz. to fully meet the water requirement of the design cropping pattern), and (iii) reliability of the project decreases and vulnerability increases when an increasing level of dependability of effective rainfall is considered. With regard to operation it is concluded that (i) field capacity concept can be fruitfully utilised for scheduling irrigations of the crops as against the total available soil water concepts since the computed irrigation requirement and the crops irrigation schedules compare well with the prevalent water needs of the crops in the area, (ii) regulation of water on the canals according to critical stages of crop growth can serve as an intermediate step towards the crop oriented irrigation management and (iii) crop oriented irrigation management wherein water requirements of crops can be closely met should be aimed at in any irrigation project.

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